REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE March 15, 1999	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE
Modeling High Frequency Semiconductor Devices Using Maxwell's Equations

5. FUNDING NUMBERS
DAAH04-95-1-0252

6. AUTHOR(S)
Samir M. El-Ghazaly

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical Engineering, Arizona State University
Tempe, AZ 85287-7206,

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 32238.13-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This is the final report on the research performed at Arizona State University and fnded by the Army Research Office. The main theme for this research was investigating and developing new apparoaches to model high-frequency Semiconductor devices using physically-based semiconductor device models and Maxwell's equations. In this research, we first replaced the conventional semiconductor device models, which are based on Poisson's Equation as a semiconductor model, with a new one that uses the full-wave electromagnetic model, derived from Maxwell's Equations Solution. We used a complete hydrodynamic model to represent the electron transport physics inside the device. This Model was used to study MM-wave MESFETs and HEMTs. Electromagnetic-wave propagation effects on the transistor performance were analyzed in detail. The newly developed model was used inside a Finite-Difference Time-Domain model to simulate a complete millimeter-wave amplifier. A hybridization technique was used to represent the passive part of the circuit (i.e., the matching network) and reduce the computational load. We also developed a new hybridization technique for simulating large electromagnetic, it is called "Time-Domain Impedance." The developed studies used for optimizing RF components and novel transmission lines. This research resulted in more than 50 publications and presentations. Four Ph.D. degrees were awarded to students supported by this research, who joined inductrial companies in US.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Modeling High Frequency Semiconductor Devices Using Maxwell's Equations

Final Report

Samir M. El-Ghazaly

March 1999

U.S. Army Research Office

DAAH04-95-1-0252

Arizona State University

Approved for Public Release;
Distribution Unlimited

THE VIEWS, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUCTED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

Table of Contents

List of Appendixes

List of Illustrations

4. Development of the Novel Simulation Approach

This project developed a new simulation scheme for investigating electromagnetic wave effects on millimeter-wave transistors and other semiconductor devices. This scheme is based on coupling a set of equations capable of accurately describing the electron transport phenomena in semiconductors, with a three-dimensional solution of Maxwell's equations. At this stage, the active device model is based on the moments of the Boltzmann's transport equation obtained by integration over the momentum space. Three equations are used; Carrier conservation equation, Momentum Conservation equation, and Energy conservation equation. These equations are coupled with a full-electromagnetic wave model. The complete set of equations are solved in time domain after discretizing it over a three dimensional mesh extending over the semiconductor material, the surrounding media, and the electrodes including the distribution pads. The coupling between the two models is established by using fields obtained from the solution of Maxwell's equations in the active device model to calculate the current densities inside the device. These current densities are used to update the electric and magnetic fields.

The funding for this program started in May, 1995. The tasks accomplished in the first year can be summarized as follows:

- The code for the obtaining the semiconductor device characteristics was completed and adjusted for coupling to the full-wave solver.
- The code for the Electromagnetic solution was developed and adapted to accept the semiconductor device equations.
- The two models were successfully merged.
- Elaborate system of absorbing boundary conditions, nonuniform mesh, electrode pads and various other improvements were introduced.

The complete code was used to investigate several electromagnetic waves and semiconductor devices interactions.

5. Significance of the New Simulator Development

We completed the development of the FIRST high frequency device simulator that combines the electromagnetic-waves with the electron transport for . This is a physically-based model, which capable of representing short gate effects and other aspects that make semiconductor devices operate at high speed/high frequencies, as well as the effects related to electromagnetic wave propagation. It will be referred to as a combined electromagnetic and solid-state (CESS) simulator. Usually, microwave devices are modeled as active devices embedded between two ideal, lossless transmission lines or in relatively simple circuit models.

Such approaches has two main drawbacks: 1) Quasi-TEM transmission lines are used, and 2) the semiconductor device model is developed in total separation from the EM wave. Therefore, direct solutions of Maxwell's equations are needed for a more accurate and general approach. The full-wave physical model used in this work allows a flexible description of the device along with the appropriate representation of simulation parameters. The application of the model to different electronic structures, such as the High Electron Mobility Transistor (HEMT), with different material profiles and boundaries is straight forward. This was accomplished and presented in our publications (please see sample of publications).

6. Simulation of a Complete Amplifier

After developing the CESS, our next goal was to simulate a microwave amplifier with the passive matching networks using the CESS model. The simulation of a complete amplifier using the Finite-Difference Time-Domain (FDTD) method requires intensive computer memory and consumes a considerable amount of time. The problem of large computer memory and time can be reduced by breaking the amplifier circuit into active and passive parts, then model the passive parts separately using the FDTD technique and combine them with the full-wave simulation of the transistor. Breaking a large circuit into sub-circuits can be achieved by using the time-domain diakoptics method or the discrete time-domain Green's function.

The microwave amplifier consists of input and output matching networks and a transistor. The input and the output matching networks are very large compared to the transistor. But the mesh size and, consequently, the FDTD stability criteria for the amplifier are severely limited by the debye length of the semiconductor. This imposes a constraint on the time step Δt of the FDTD algorithm, which becomes on the order of 10^{-17} seconds. If the input and the output matching networks were to be simulated using this criteria, it would take so long time to simulate the amplifier circuit that it becomes almost impossible using the current computers. In this research, a full-wave analysis is performed to simulate the microwave amplifier with two tuned coplanar wave guides (CPW) as matching networks (see Fig. 1). The whole amplifier is divided into three regions. The simulation of each region is performed individually and coupled to the next stage properly with all the required information from the preceding stage. This technique enables one to use large space step, and hence, large time step in matching networks. The computer simulation time is reduced drastically compared to the method incorporating the non-uniform mesh for the whole amplifier. The computer memory requirement is also lowered by approximately 66 % at a certain time.

Our group accomplished this major milestone in the process of developing physical models for microwave circuits in 1997. It should be noted that this is the first time a complete amplifier is modeled using the physical-based simulations. This is the only simulation relating the high frequency amplifier performance to the microscopic electronic characteristics of the active device and the electromagnetic matching network simultaneously. Several research groups, in US and abroad, are developing, or attempting to develop, similar simulators following our approach.

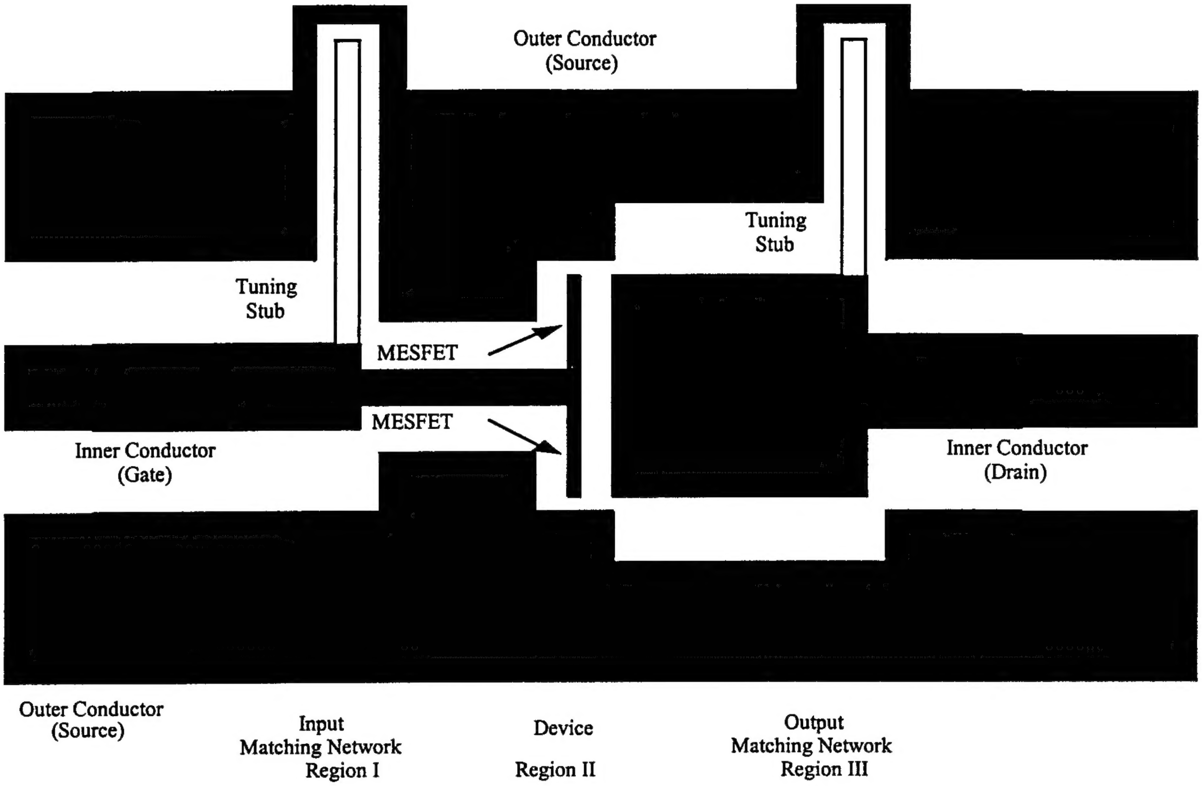


Fig. 1. GaAs transistor amplifier with CPW matching networks (a) Schematic (b) Detailed diagram.

7. Comprehensive Analysis of Discontinuity Effects on High Frequency Transistors

In conventional high frequency GaAs transistors, several configurations are implemented. The layout of the physical device affects its performance, especially at high frequency of operation. Typical configurations for a MESFET or HMET are the interdigitated construction and the four-finger. It is clear that the electrodes of the active device form a guided wave structure. At high frequency, those electrodes have to be treated as transmission lines. This transmission lines can be regarded as slot lines or coplanar waveguide, which forms a discontinuity at the input and output ports of the device. Therefore, the input and output impedance must be carefully analyzed. A common practice in analyzing the discontinuity effects on active devices is to analyze the passive structure separately from the behavior of the real active device. This approach does not take into account the interaction between the wave propagating along the device electrodes and the electron transport in the active device and their effects on the device characteristics. On the other hand, it is very difficult to determine the discontinuity effects from measurement. This situation prevents, in many cases, the possibility of matching the FET at all. Consequently, the true performance of the FET might be unknown.

In this research, an algorithm, that deals with the electromagnetic wave and the electrodynamics inside the transistor simultaneously, is used to study the discontinuity effects on the high frequency performance of MESFET transistor. Although the method is difficult to formulate, it allows more accurate, flexible and realistic conditions to be investigated. The physical semiconductor model is based on the complete hydrodynamic system. The full-wave solution is used to update the ac fields inside the device. These two schemes are blended together using the current/field relation. The s-parameters are calculated for different device configurations. Very informative results regarding the effects of discontinuities on millimeter-wave transistor performance were generated. They are useful for device optimization and developing new designs that exploits the wave propagation effects.

8. Extending the applications to quasi-optical power combiners

The power and the versatility of the FDTD technique has been limited by its computational cost, specially when it comes to the simulation and optimization of circuits with large areas. In addition, the method has accuracy and stability problems when simulating structures which require variable mesh coarseness, like in the case of simulating circuits with active devices. The diakoptics technique overcomes these difficulties by breaking down large structures into smaller ones and characterizing each subsection with its impulse response. The analysis of the full structure is then achieved by subsequently interconnecting the individual responses together via a convolution process. This method is well established for the analysis of steady state-networks.

The purpose of this research is to expend and validate time domain diakoptics to 3D structures to extend this approach to millimeter-wave quasi-optical systems. Techniques to save memory and computational time are investigated and developed. Validation of this technique is illustrated by comparing the results obtained using this method with those obtained by using FDTD simulation of the full structure. Excellent agreement was obtained. This technique was applied to the antenna used in a two-dimensional quasi-optical power combiner. The objective is to model the entire structure, including the active devices, using the combined electromagnetic solid-sate simulator.

9. Development of the 3-D diakoptic Approach for circuit simulations

The power and the versatility of the FDTD technique has been limited by its computational cost, specially when it comes to the simulation and optimization of circuits with large areas. In addition, the method has accuracy and stability problems when simulating structures requiring variable mesh coarseness, like in the case of simulating circuits with active devices. The diakoptics technique overcomes these difficulties by breaking down large structures into smaller ones and characterizing each subsection with its impulse response. The analysis of the full structure is then achieved by subsequently interconnecting the individual responses together via a convolution process. Our contribution to this subject is two fold: First, we expended and validated time domain diakoptics for 3-D microwave structures (validation of this technique is illustrated by comparing the results obtained using this method with those obtained by using FDTD simulation of the full structure). Second, We used the FDTD/diakoptics method to

perform a full-wave simulation of the passive structure of quasi-optical amplifier used in two-dimensional power combining systems. To limit the memory requirement the convolution process is performed only at few selected points of the port mesh. The field distribution at the rest of the mesh points is approximated by modulating the calculated fields with the steady state field distribution. To reduce the heavy burden of the convolution operation, the Prony method is used to approximate the impulse responses and generate a fast recursive convolution. Details of this method can be found in our published papers listed hereafter.

10. Low Loss Air-Gap Transmission Lines and Spiral Inductors for MMICs Using Glass Microbump Bonding Technique

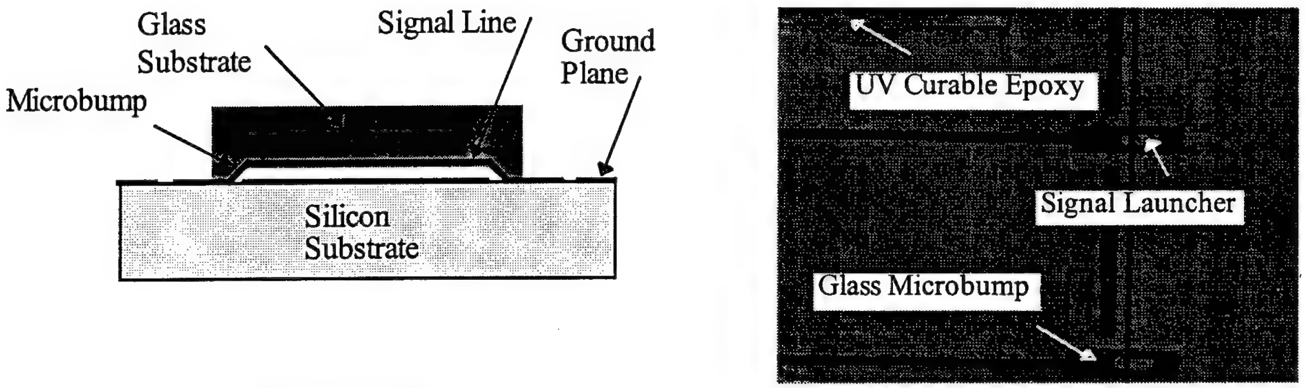
One of the byproducts of our research is to use knowledge and insight gained to develop better active and passive devices for high frequency operations. For example, new types of transmission lines, called air-gap lines, were developed, simulated, fabricated and tested in our group. These are microwave transmission lines deposited on glass superstrates and then connected to active devices, fabricated on lossy substrates as usual, using a new technology known as Glass Microbump Bonding Technique GMBB (also developed in our group.) The low-loss characteristics is one of the main advantages of the new air-gap transmission lines. Moreover, air-gap spiral inductor structures have been fabricated and integrated with semiconductor substrates using the same technology. Spiral inductors using air-gap structures have the advantages of low losses, and low parasitic capacitance compared to conventional inductors on doped silicon semiconductor substrate. Stacked air-gap spiral inductors on GaAs substrates using GMBB techniques also can reduce the inductor area. Because the glass microbump bonding techniques are simple, this bonding technique provides an alternative integration approach for monolithic microwave integrated circuits (MMICs). Experimental results of air-gap spiral inductor on both silicon and GaAs substrates were obtained.

11. Technology Transfer

The interest in this novel technique for analyzing semiconductor devices prompted us to widely disseminate the information. More than 50 archival journal papers, dissertations, and presentations has resulted from this research. There are listed in the following sections.

All the personnel funded from this project has joined, or accepted offer, from industrial companies in US (The P.I. is not included). Their names and current employers are as follows:

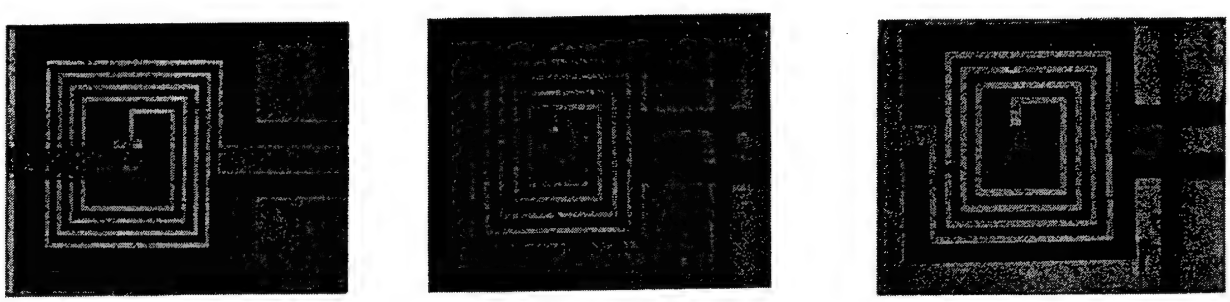
1. Mohamed A. Megahed, Ph.D., Post Doctoral Research Associate, joined "Peregrine Semiconductors."
2. S.M. Sohel Imtiaz, Ph.D. Graduate Research Assistant, joined "Micro Linear."
3. Jeff Cheuang, Ph.D., Graduate Research Assistant, joined "M/A-COM, Inc."
4. Samir Hammadi, Ph.D expected in May 99. Graduate Research Assistant, Has already received some offers from companies in US, decision pending.



(a) Side View

(b) Top View

Fig. 2. Air-gap microstrip line (AGML) structure fabricated using GMBB techniques.



(a) (b) (c)

Fig. 3. Photographs of various types of inductors. (a) Conventional inductor. (b) Air-gap inductor. (c) Stacked inductor.

12. Conference and Workshop Presentations

[1] M. Alsunaidi and S. El-Ghazaly, "Electromagnetic Wave Effects on Millimeter Wave Semiconductor Devices;" *PIERS 1995- Progress in Electromagnetic Research Symposium*, Seattle, WA , P. 795, July 1995.

[2] R. Grondin, I.-S. Lim and S. El-Ghazaly, "Parallel Processing of Full-Wave Electromagnetic Models of Ultrafast Photoconductive Switching;" *PIERS 1995- Progress in Electromagnetic Research Symposium*, Seattle, WA, P. 801, July 1995.

[3] S.M. Sohel Imtiaz, M.A. Alsunaidi, M.A. Megahed and S. El-Ghazaly, "Electromagnetic Wave Effects on MODFETs;" *1996 National Radio Science Meeting- U.S. National Committee of URSI*, Boulder, Co, p. 155, January 1996.

[4] M.A. Megahed and S. El-Ghazaly, "Extrinsic Parameters Modeling of High Frequency Semiconductor Transistors;" *1996 National Radio Science Meeting- U.S. National Committee of URSI*, Boulder, Co, p. 157, January 1996.

[5] S.M. El-Ghazaly and G. Pan, "The Challenges in Electromagnetic Modeling of High Speed Electronics Packaging, *1996 National Radio Science Meeting- U.S. National Committee of URSI*, Boulder, Co, p. 251, January 1996.

[6] T. LaRocca, A.C. Reyes and S. El-Ghazaly, "Analysis of Electromagnetic Wave Propagation on Coplanar Waveguides on Doped Semiconductor Substrates;" *Proc. of the 1996 IEEE MTT-s Int. Microwave Symp.*, San Francisco, CA, vol. 1, pp. 295-298, June 1996.

[7] S.M. Sohel Imtiaz, M.A. Alsunaidi and S. El-Ghazaly, "Performance Comparison of MODFET and MESFET Using Combined Electromagnetic and Solid-State Simulator;" *Proc. of the 1996 IEEE MTT-s Int. Microwave Symp.*, San Francisco, CA, vol. 3, pp. 1783-1786, June 1996.

[8] S. El-Ghazaly and M. Golio, "Challenges in Modern Wireless Personal Communications;" **Invited Paper** in *13th National Radio Science Conf. (NRSC'96)*, Cairo, pp. RV3 1-13, March 1996.

[9] M. Golio and S. El-Ghazaly "Emerging RF Issues for Modern Personal Commercial Communication Systems: Power Amplifiers for Portable Cellular Applications;" **Invited Paper** in *13th National Radio Science Conf. (NRSC'96)*, Cairo, pp. RV3 14-23, March 1996.

[10] S.M. El-Ghazaly, M. Megahed, C. Balanis, and P. Blakey, "Progress of Electromagnetic Modeling of Device and Circuit Interconnects;" **Invited Paper** in *PIERS 1996- Progress*

in Electromagnetic Research Symposium, Innsbruck, Austria, P. 73, July 1996.

[11] M. Megahed and S. El-Ghazaly, "Modeling RF Characterizations of High Frequency Transistors;" XXVth General Assembly of the International Union of Radio Science, Lille, France, p. 590, Sept. 96.

[12] T.R. LaRocca, AC. Reyes, V. Nair, S. El-Ghazaly, and L. Mang; "Coplanar Waveguides on Semiconductor Substrates for R.F. Applications;" XXVth General Assembly of the International Union of Radio Science, Lille, France, p. 593, Sept. 96.

[13] S.M. Sohel Imtiaz and S.M. El-Ghazaly, " Characterization of Microwave Transistors as a Function of Frequency, Temperature and Device Width;" Asia-Pacific Microwave Conference, New Delhi, India, Dec. 1996.

[14] S.M. Sohel Imtiaz and S.M. El-Ghazaly, " Microwave and Millimeter-Wave Performance of FET Amplifiers Using Combined Electromagnetic and Solid-State Simulator;" Asia-Pacific Microwave Conference, New Delhi, India, Dec. 1996.

[15] S. El-Ghazaly, S. Goodnick and James Harvey, "Challenges in Global Modeling of Millimeter-Wave Circuits;" **INVITED PAPER**, Proc. of Dixiemes Journees Nationales Microondes, St. Malo, France, PP 3INV1-7, May 1997.

[16] J. Cheuang, S. El-Ghazaly, D. Schroder, Y. Zhang, G. Maracas, and A. Reyes, "Air-Gap Transmission Lines for OEICs and MMICs Using Glass Substrates;" Proc. of the 1997 IEEE MTT-s Int. Microwave Symp., Denver, CO, pp. 265-268, June 1997.

[17] S. El-Ghazaly and T. Itoh, "Electromagnetic Interfacing of Semiconductor Devices and Circuits;" **INVITED PAPER**, Proc. of the 1997 IEEE MTT-s Int. Microwave Symp., Denver, CO, pp. 151-154, June 1997.

[18] M. Megahed and S. El-Ghazaly, "Discontinuity Effects on High Frequency Transistors;" Proc. of the 1997 IEEE MTT-s Int. Microwave Symp., Denver, CO, pp. 609-612, June 1997.

[19] S.M. Sohel Imtiaz and S.M. El-Ghazaly, "Physical Simulation of Complete Millimeter-Wave Amplifiers Using Full-Wave FDTD Technique;" Proc. of the 1997 IEEE MTT-s Int. Microwave Symp., Denver, CO, pp. 79-82, June 1997.

[20] S.M. Hammadi and S. El-Ghazaly, "Extending FDTD/Convolution Techniques to 3-D Microwave Structures;" IEEE Antennas and Propagation Society International Symposium 1997, Montreal, Canada, pp. 2180-2183, July 1997.

[21] S.M. Hammadi and S. El-Ghazaly, "Electromagnetic Wave Effects on High Frequency Transistors;" 1997 North American Radio Science Meeting, Montral, Canada, p. 348, July 1997.

[22] S.M. Hammadi and S. El-Ghazaly, "Simulation of Large Electromagnetic Structures with an Application to Quasi-Optical Amplifier;" Proc. of the 1997 European Microwave Conf., Jerusalem, Israel, vol. 2, 870-876, Sept. 1997.

[23] J.C.P. Chuang, S.M. El-Ghazaly, and Y.H. Zhang, "Glass Air-Gap Transmission Lines on Silicon for Microwave Integrated Circuits;" Proc. of the 1997 European Microwave Conf., Jerusalem, Israel, Sept. 1997.

[24] J.C.P. Chuang, S.M. El-Ghazaly, and D.K. Schroder, "Experimental Study of Spiral Inductors on Silicon Substrates;" *1998 National Radio Science Meeting- U.S. National Committee of URSI*, Boulder, Co, p. 2, January 1998.

[25] S. Hammadi and S. El-Ghazaly, "FDTD Simulation of Electrically Large MMICs Using Domain Decomposition Techniques;" *1998 National Radio Science Meeting- U.S. National Committee of URSI*, Boulder, Co, p. 61, January 1998.

[26] J.Chuang, S. El-Ghazaly, N. El-Zein, V. Nair, G. Maracas, and H. Goronkin, "Low Loss Air-Gap Spiral Inductors for MMICs Using Glass Microbump Bonding Technique;" *Proc. of the 1998 IEEE MTT-s Int. Microwave Symp.*, Baltimore, MD, pp. 131-134, June 1998.

[27] M. Toupikov, G. Pan, and S. El-Ghazaly, "Global Modeling of Microwave Devices Using Wavelets;" *Proc. of the 1998 IEEE MTT-s Int. Microwave Symp.*, Baltimore, MD, pp. 263-266, June 1998.

[28] S.M. El-Ghazaly, "New Trends in Modeling Electromagnetic-Wave Interactions with Semiconductor Devices and Circuits;" **Invited Paper** *PIERS-Progress in Electromagnetics Research Symposium*, Nantes, France, Vol. 2, p. 611, July 1998.

[29] S. Hammadi and S. El-Ghazaly, "Characteristics of Air-Bridged Transistors;" *1999 National Radio Science Meeting- U.S. National Committee of URSI*, Boulder, Co, p. 216, January 1999.

[30] Samir Hammadi and Samir El-Ghazaly, "Recent Trends in Global Simulation of Millimeter-Wave Devices and Circuits;" *SPIE -Millimeter-Wave Materials, Devices, and Components (SD25)*, Denver, CO, July 1999.

[31] S. Hammadi and S. El-Ghazaly, "Simulation of Large Electromagnetic MMICs Using Time-Domain Impedance Concept;" to appear in *Proc. of the 1998 IEEE MTT-s Int. Microwave Symp.*, Anaheim, CA, June 1999.

[32] S. Goasguen, and S. El-Ghazaly, "A Global Modeling Approach Using Artificial Neural Networks;" to appear in *Proc. of the 1998 IEEE MTT-s Int. Microwave Symp.*, Anaheim, CA, June 1999.

[33] S. El-Ghazaly, **Invited Paper**, "Status of Global Modeling of Millimeter-Wave Circuits;" to be presented in <u>*XXVI General Assembly of International Union of Radio Science*</u>, Toronto, Canada, Aug. 1999.

Workshops

[34] S. El-Ghazaly and M. Megahed, "Electromagnetic Waves in Semiconductor Devices;" IEEE International Microwave Symposium Workshop on Device Field Interactions for Future Advances in Microwave and RF Circuits, San Francisco, CA, June 1996.

[35] S. El-Ghazaly and T. Itoh, "Novel Methodologies for Device Modeling and Circuit CAD;" Workshop on Novel Methodologies for Device Modeling and Circuit CAD, IEEE International Microwave Symposium, Anaheim, CA, June 1999.

[36] R. Grondin, S. El-Ghazaly and S. Goodnick, "Incorporating Full-Wave Electromagnetics into Semiconductor Device Models;" Workshop on Global Modeling, IEEE APS/URSI International Symposium, Orlando FL, July 1999.

13. Archival Journal Papers

A Special Issue of The IEEE Transactions on Microwave Theory and Techniques is devoted for the topic of Global Modeling of Millimeter-Wave Circuits. This new device modeling approach was the main motivation behind this special issue. The P.I. is a Guest Editor. It is scheduled to appear in June 99.

The following journal papers report interesting results from this research project.

[37] M.A. Alsunaidi, S.M. S. Imtiaz and S.M. El-Ghazaly, "Electromagnetic Wave Effects on Microwave Transistors Using a Full-Wave High-Frequency Time-Domain Model;" <u>*IEEE Trans. Microwave Theory Tech*</u>, vol. 44, no. 6, pp. 799-808, June 1996.

[38] M.A. Alsunaidi, S.M. Hammadi and S.M. El-Ghazaly, "Parallel Implementation of a Two-Dimensional Hydrodynamic Model for Microwave Semiconductor Devices Including Inertia Effects in Momentum Relaxation;" <u>*International Journal of Numerical Modeling: Electronic Networks, Devices, and Fields*</u>, vol. 10, pp. 107-119, 1997.

[39] S.M. Sohel Imtiaz and S.M. El-Ghazaly, "Global Modeling of Millimeter-Wave Circuits: Electromagnetics Simulation of Amplifiers;" <u>*IEEE Trans. Microwave Theory Tech*</u>, vol. 45, no. 12, pp. 2208-2216, Dec. 1997.

[40] S.M. Sohel Imtiaz, S.M. El-Ghazaly, and R.O. Grondin, "Advantages of Semiconductor Device Simulator Combining Electromagnetic and Electron Transport Models;" *VLSI Design*, vol. 8, nos 1-4, pp. 495-500, 1998 .

[41] I.-S. Lim, R.O. Grondin and S.M. El-Ghazaly, "Ensemble Monte Carlo and Full-Wave Electrodynamic Models Implemented Self-Consistently on a Parallel Processor Using Perfectly Matched Layer Boundary Conditions;" VLSI Design, vol. 8, nos 1-4, pp. 129-133, 1998.

[42] S.M. Sohel Imtiaz and S. El-Ghazaly, "Performance of MODFET and MESFET: A Comparative Study Including the Equivalent Circuits Using Combined Electromagnetic and Solid-State Solver;" *IEEE Trans. Microwave Theory Tech*., vol. 46, no. 7, pp. 923-931, July 1998.

[43] J.C.P. Chuang and S.M. El-Ghazaly; "Integration of Air-Gap Transmission Lines on Doped Silicon Substrate Using Glass Microbump Bonding Techniques;" *IEEE Trans. Microwave Theory Tech*., vol. 46, no. 11, pp. 1850-1855, Nov. 1998.

[44] S. Hammadi, R.O. Grondin, S. El-Ghazaly and S. Goodnick, "Full-Wave Electromagnetic Simulation of Millimeter-wave Active Devices and Circuits;" Accepted for publication in *Annales des Telecom*.

[45] R.O. Grondin, S.M. El-Ghazaly and S. Goodnick, "Global Modeling of Charge Transport in Semiconductors and Full-Wave Electromagnetics;" Accepted for publication in *IEEE Trans. Microwave Theory Tech*, June 1999.

[46] S. Hammadi and S. El-Ghazaly, "Air-Bridged Gate MESFET Transistor: A New Structure to Reduce Wave Propogation Effects in High Frequency Transistors;" Accepted for publication in *IEEE Trans. Microwave Theory Tech*, June 1999.

14. Book Chapters

[47] S. El-Ghazaly, "Chapter 9: Modeling of Millimeter Wave Devices from Consideration of Charge Transport;" *Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method*, edited by ARTECH HOUSE, INC., Norwood, Massachusetts, July 1998.

15. Dissertations

[48] M. Alsunaiedi, Ph.D., May 1995, Simulation of High-Frequency Semiconductor Devices Using a Full Electromagnetic Wave Model.

[49] S.M. Sohel Imtiaz, Ph.D., August 1997, Physical Simulation of High Frequency Semiconductor Devices and Amplifier Circuits.

[50] Jeff C.P. Chuang, Ph.D., Dec. 1998, Glass Microbump Structures for Optoelectronic and Millimeter-Wave Circuits.

[51] S. Hammadi, Ph.D. (Expected: May 99), Global Modeling of Quasi-Optical Millimeter-Wave Power Combiners.

16. Special Effort in Information Dissemination

Besides this long list of conference and journal papers, the P.I. devoted a special attention to widely disseminate the information and the results generated from this research. This is a particularly important aspect of this project given its novelty, which necessitates that the wide majority of the microwave and RF community need to be informed about it. This effort included organizing special sessions in international conferences, inviting speakers, organizing panel discussions, and workshops. This wide dissemination effort resulted in a special invitation to become an editor of a special issue of the IEEE Transactions on Microwave Theory and Techniques on this topic, with two other colleagues. This special issue will appear in June 1999.

It has been observed that several groups all over the world recognized the importance of this approach and directed their research to it. Continuously increasing number of conference and journal papers are being published. It is only a matter of time.

Appendix I

Copies of Selected Publications

1. A Global Modeling Approach Using Artificial Neural Network
2. Global Modeling of Millimeter-Wave Circuits: Electromagnetics Simulation of Amplifiers
3. Integration of Air-Gap Transmission Lines on Doped Silicon Substrate Using Glass Microbump Bonding Techniques
4. Parallel Implementation of a Two-Dimensional Hydrodynamic Model for Microwave Semiconductor Devices Including Inertia Effects in Momentum Relaxation